THE CO PROTOSTELLAR OUTFLOWS OF 27 PROTOSTARS

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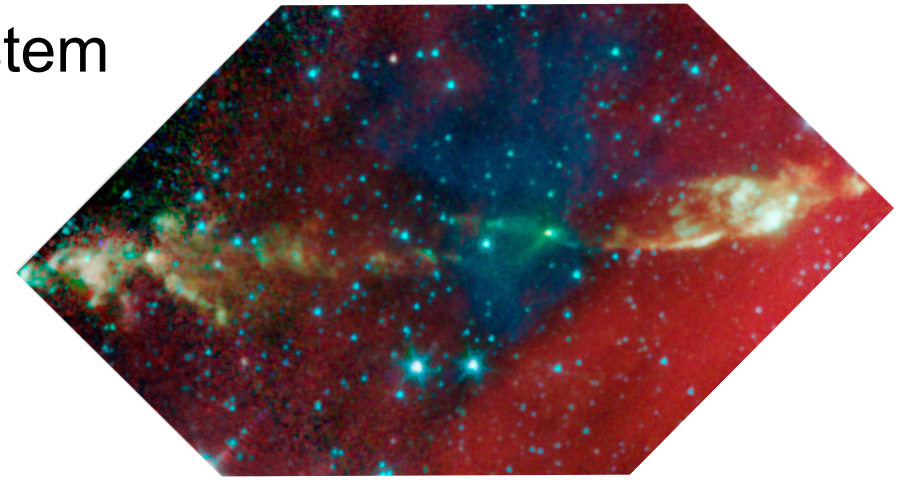
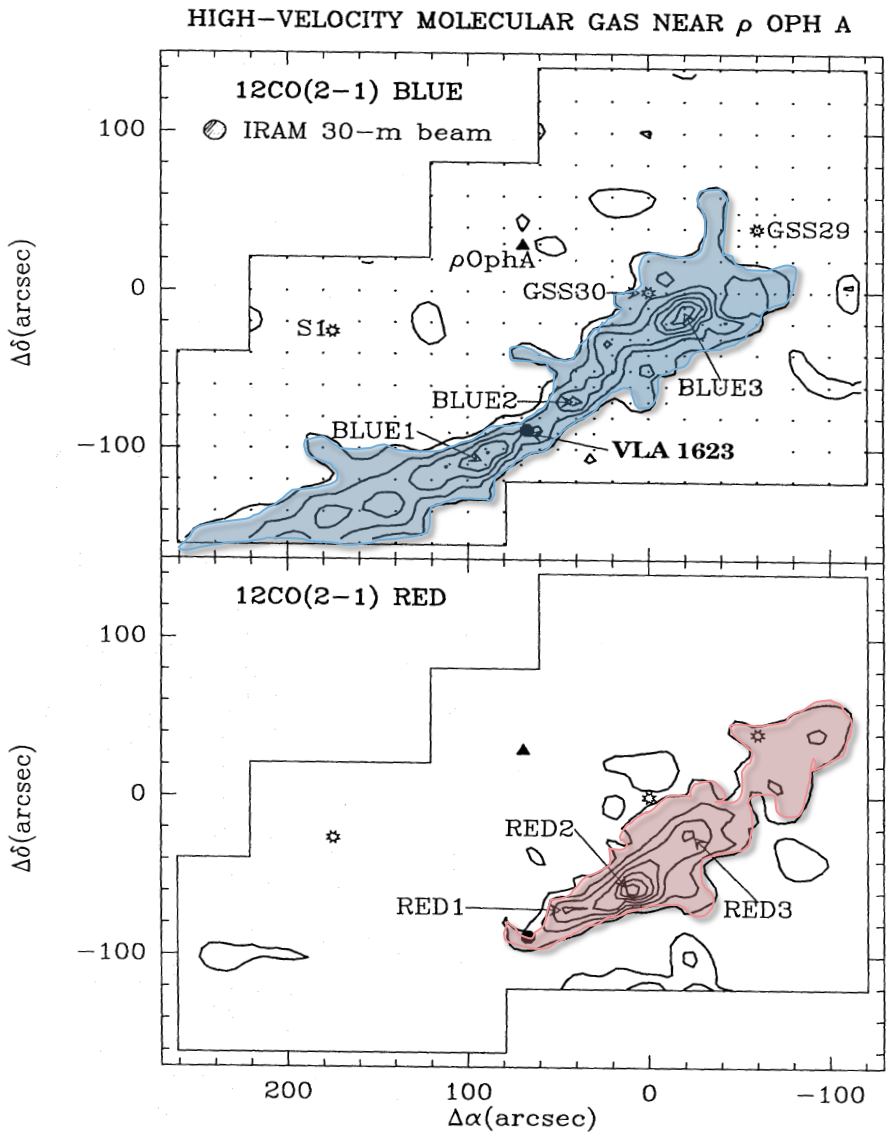
Molecular Outflows

- Found in both low- and high-mass protostars
- Helped lead to discovery of youngest class of protostars
- Accretion driven
- Can alter envelope environment
- Allow for energetics of the system to be calculated



Images: Tobin et al. (2010)



Andre et al. (1990)

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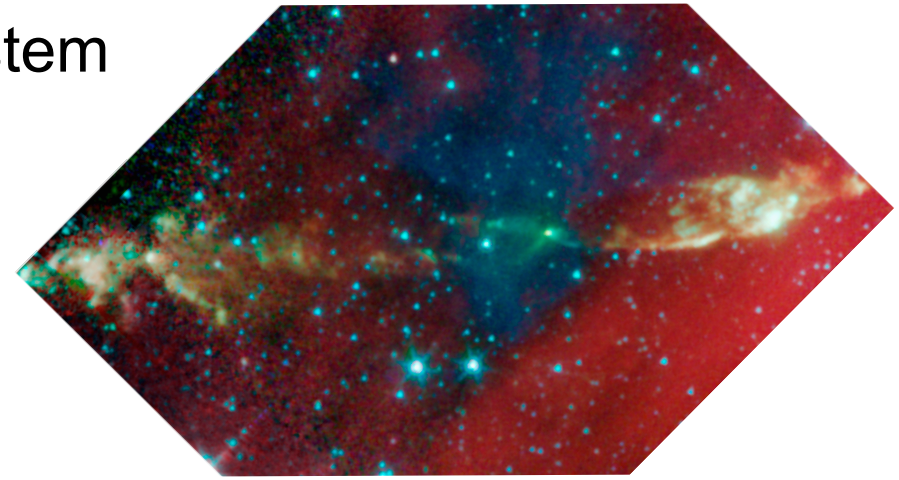
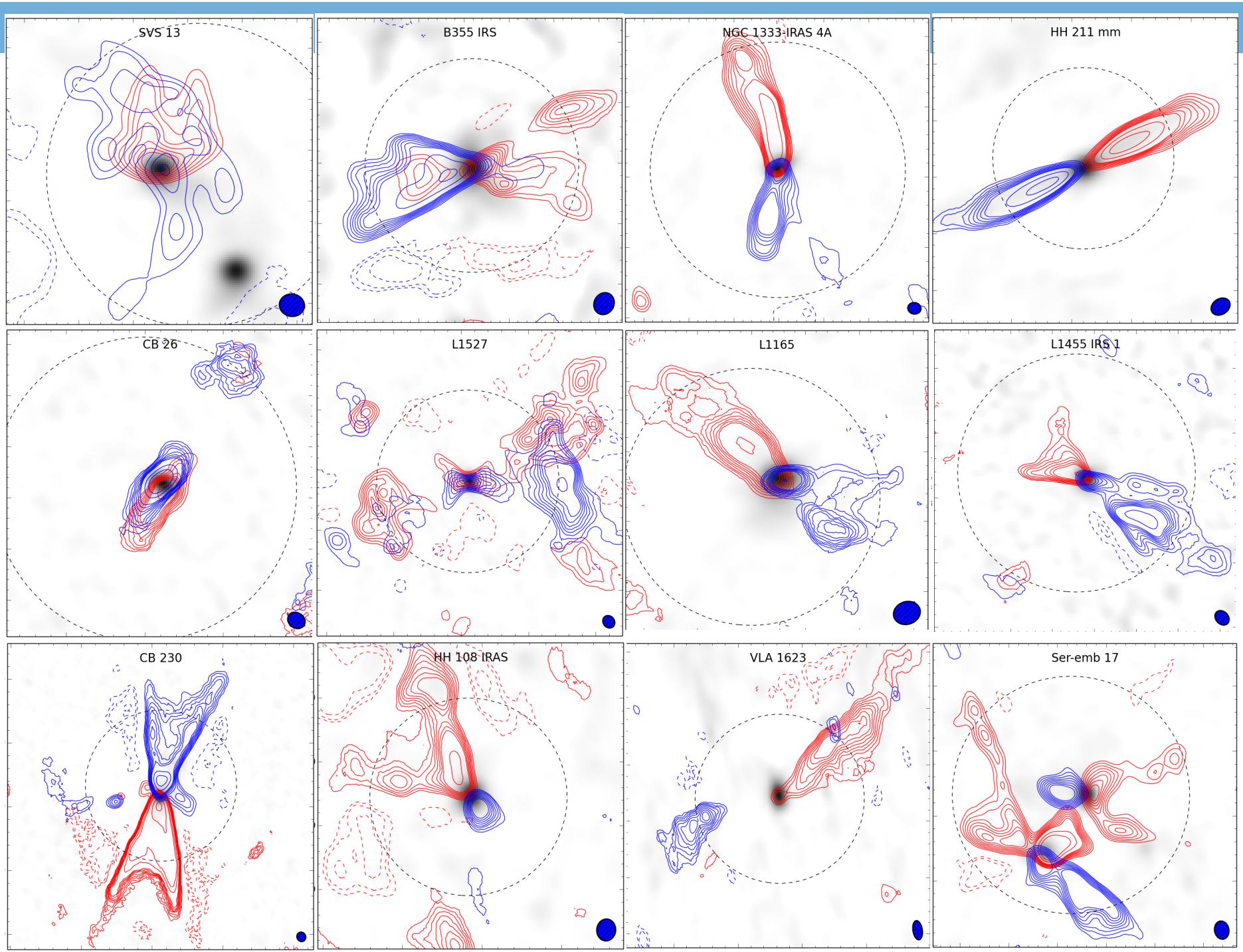


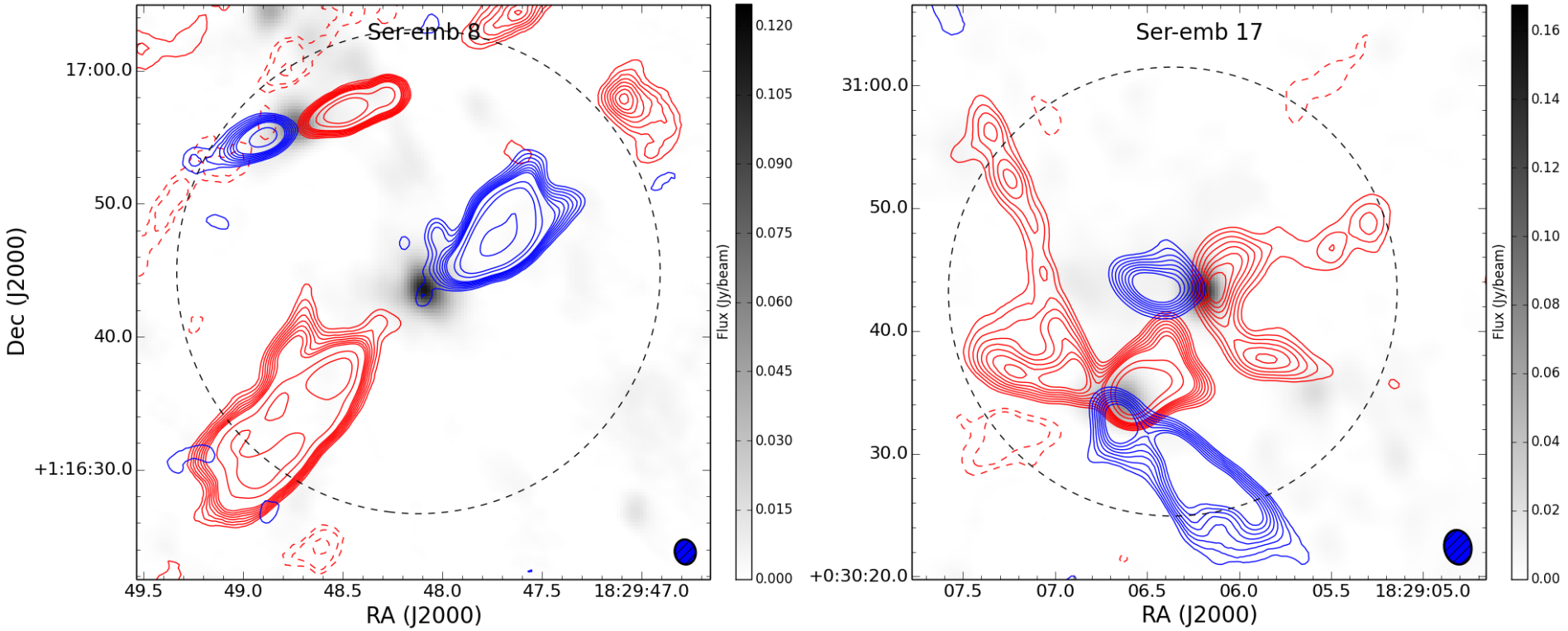
Images: Tobin et al. (2010)

Data

- CO J=(2→1) at 230.538 GHz (~1 mm)
- CARMA (C, D, E arrays with ~2-10” resolution)
- TADPOL Survey (Hull et al. 2014)
  - Single-pointings
  - Outflow orientation acts as rotation axis indicator

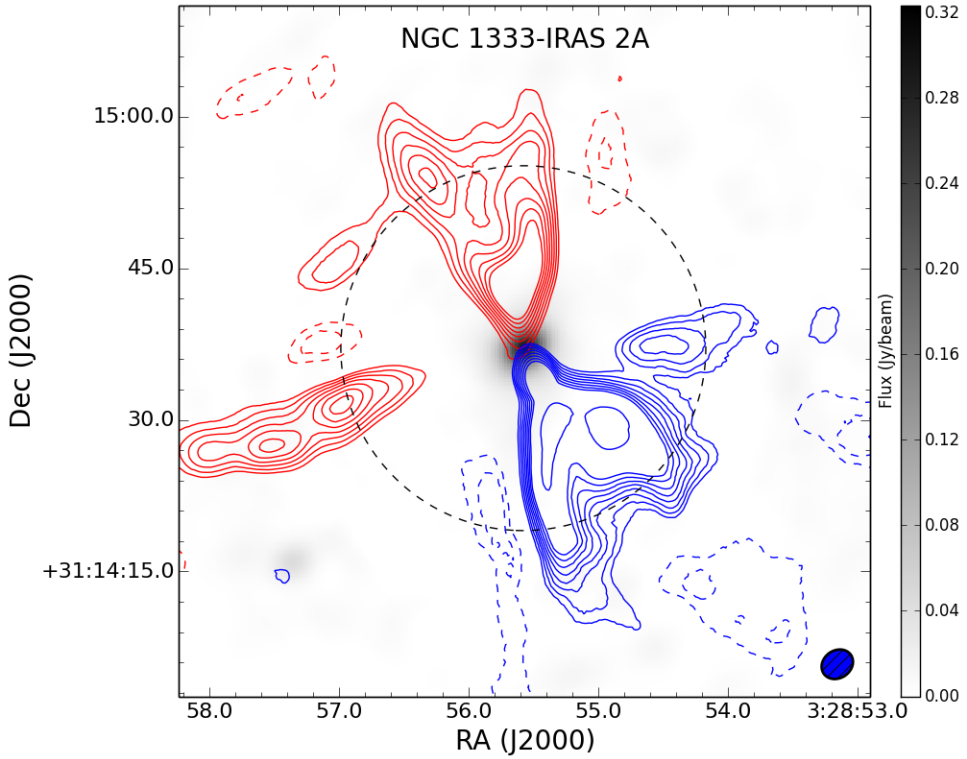

SVS 13
B355 IRS
NGC 1333-IRAS 4A
HH 211 mm
CB 26
L1527
L1165
L1455 IRS 1
CB 230
HH 108 IRAS
VLA 1623
Ser-emb 17

Ser-Emb 8 & Ser-Emb 17



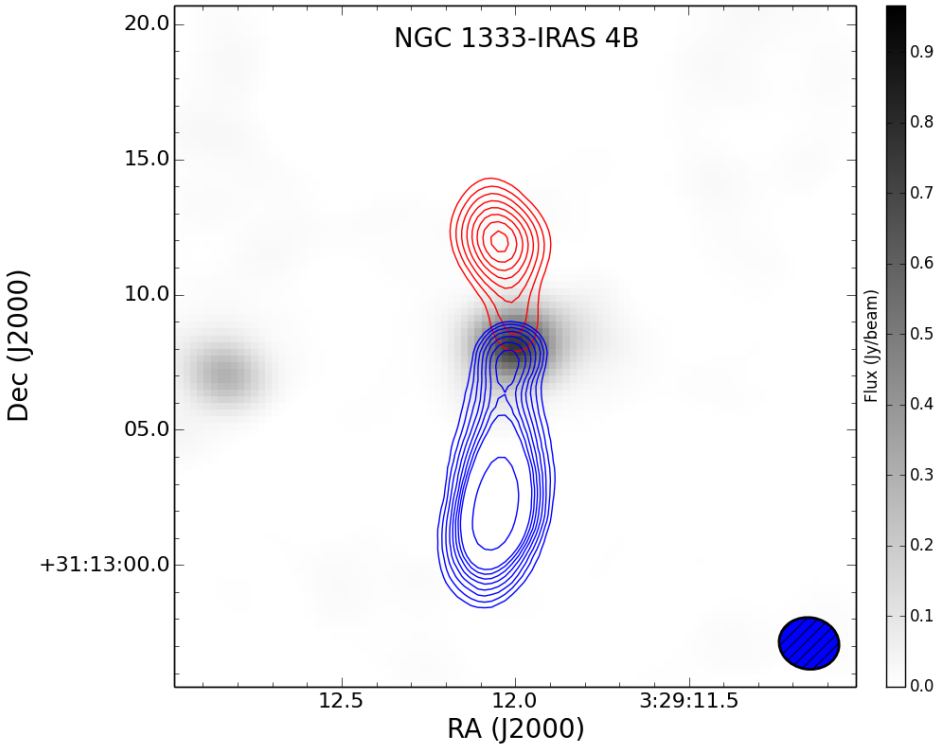
- d ~ 415 pc

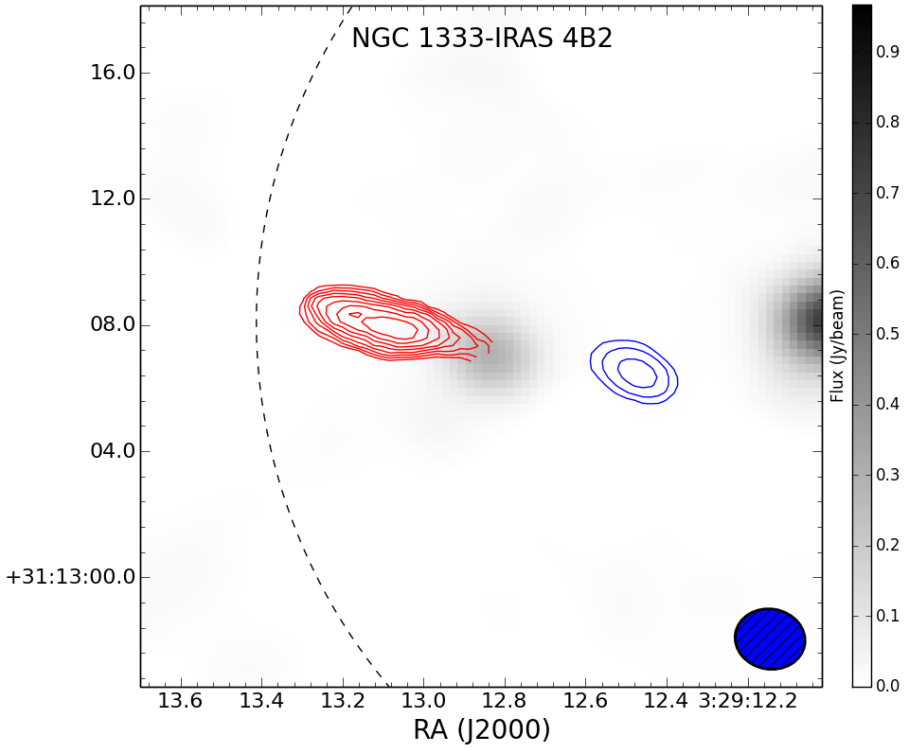
NGC 1333-IRAS 2A



- d ~ 320 pc
- Binary on subarcsecond scales detected (Tobin et al. 2014 in prep)

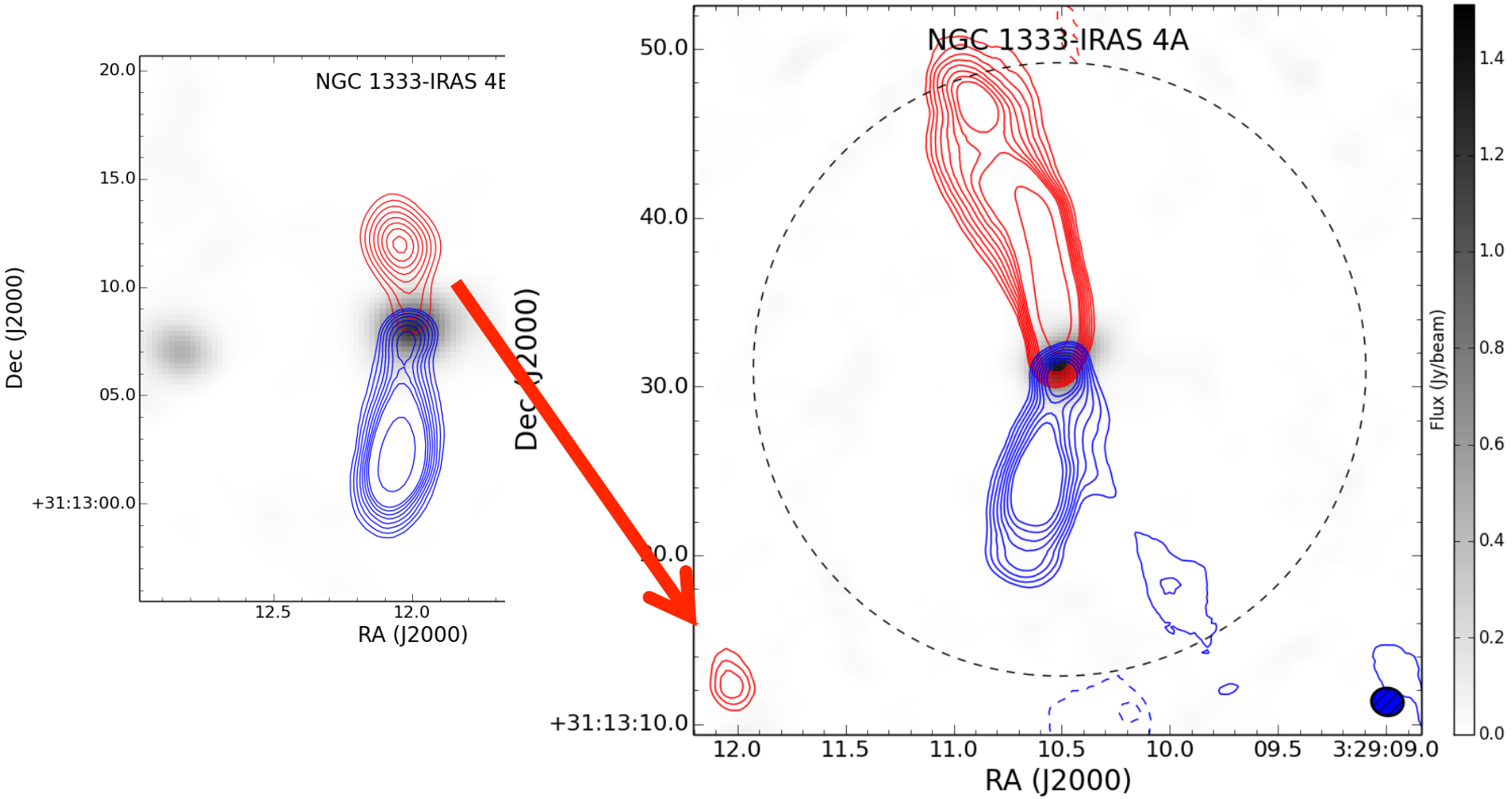
NGC 1333-IRAS 4B

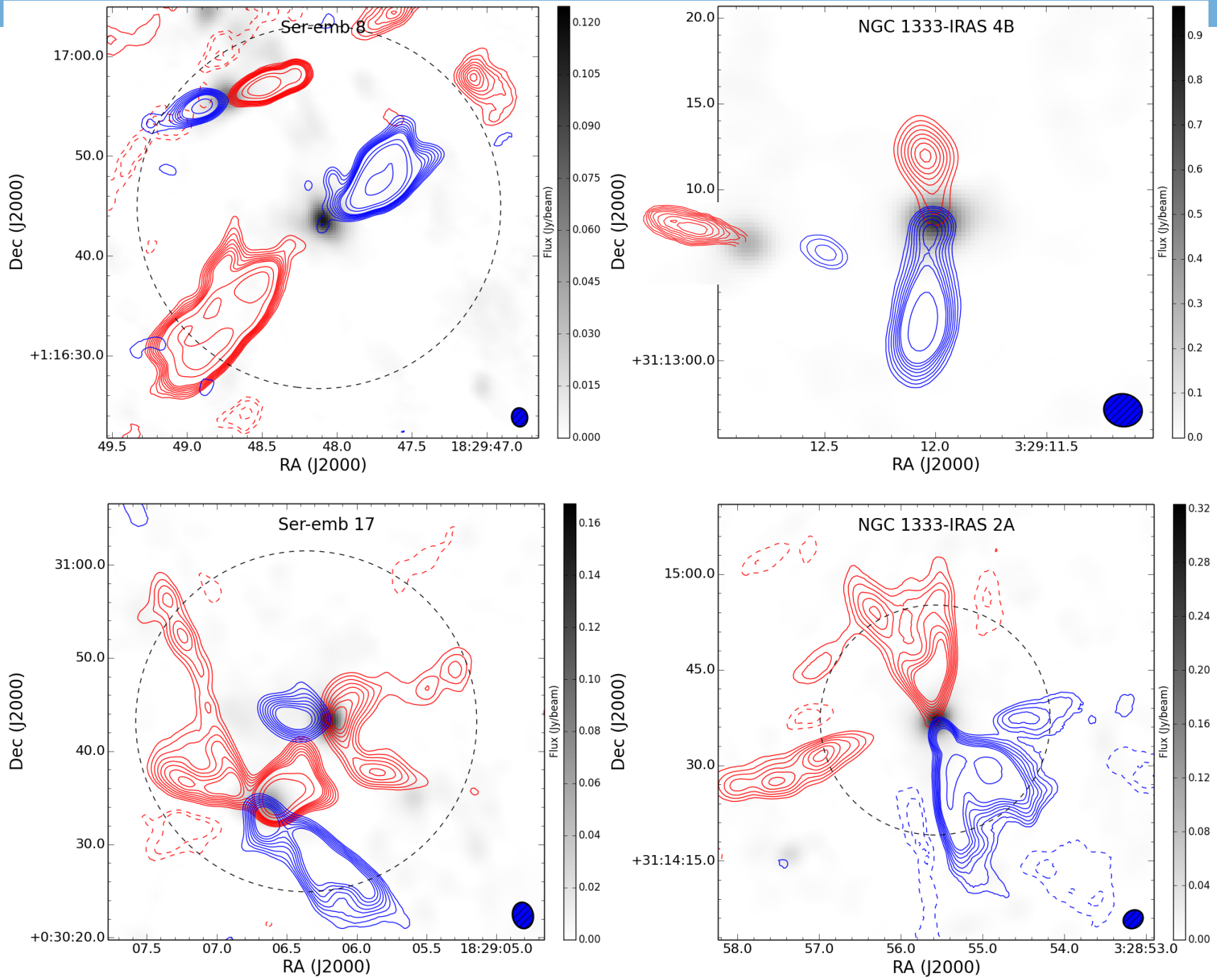




- d ~ 320 pc

NGC 1333-IRAS 4B



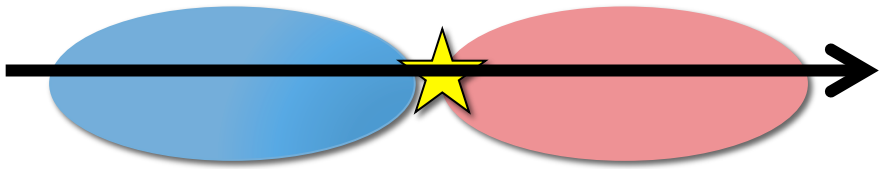

Ser-emb 8
17:00.0
50.0
40.0
+1:16:30.0
Dec (J2000)
49.5
49.0
48.5
48.0
47.5
18:29:47.0
RA (J2000)
Flux (Jy/beam)
0.120
0.105
0.090
0.075
0.060
0.045
0.030
0.015
0.000
NGC 1333-IRAS 4B
20.0
15.0
10.0
+31:13:00.0
Dec (J2000)
12.5
12.0
3:29:11.5
RA (J2000)
Flux (Jy/beam)
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
Ser-emb 17
31:00.0
50.0
40.0
30.0
+0:30:20.0
Dec (J2000)
07.5
07.0
06.5
06.0
05.5
18:29:05.0
RA (J2000)
Flux (Jy/beam)
0.16
0.14
0.12
0.10
0.08
0.06
0.04
0.02
0.00
NGC 1333-IRAS 2A
15:00.0
45.0
30.0
+31:14:15.0
Dec (J2000)
58.0
57.0
56.0
55.0
54.0
3:28:53.0
RA (J2000)
Flux (Jy/beam)
0.32
0.28
0.24
0.20
0.16
0.12
0.08
0.04
0.00

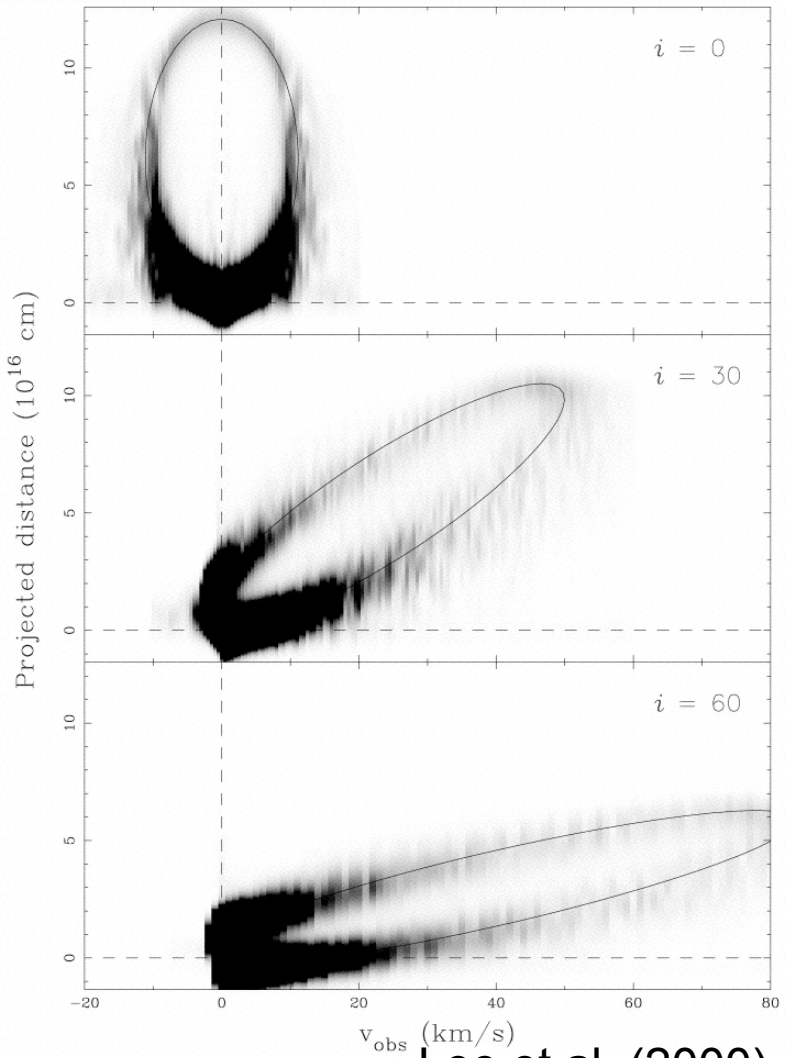
Binaries

- Outflow axes of binaries are not often aligned
  - Binary formation processes in which disks are expected to be coplanar (such as fragmentation of a rotating cloud or disk fragmentation) are disfavored
  - Other formation processes (such as capture) are not ruled out
- **May also indicate enough time has passed for significant evolution**

Position-Velocity (PV) Diagrams

- The shapes of PV diagrams can constrain the driving mechanism of the outflow (Lee et al. 2000)
- **Wind-driven outflow**
  - The PV diagram of the swept shell along the outflow axis shows a lobe structure or a tilted parabola

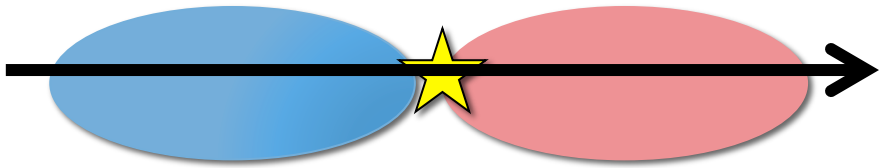


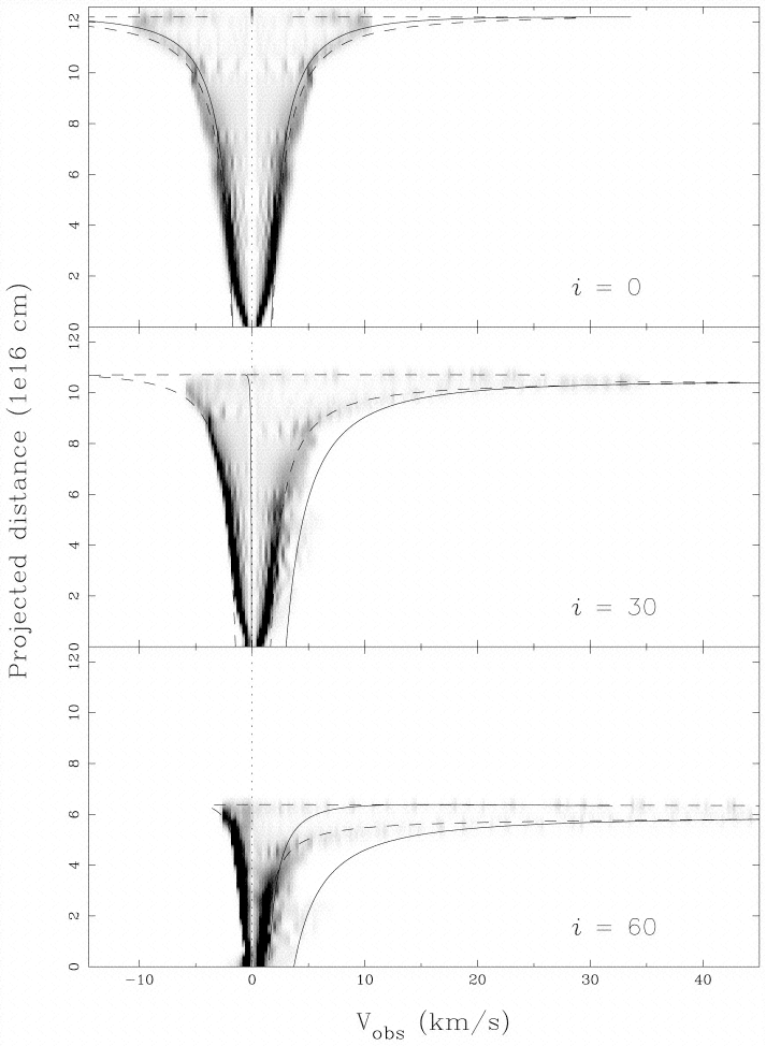


Lee et al. (2000)

Position-Velocity (PV) Diagrams

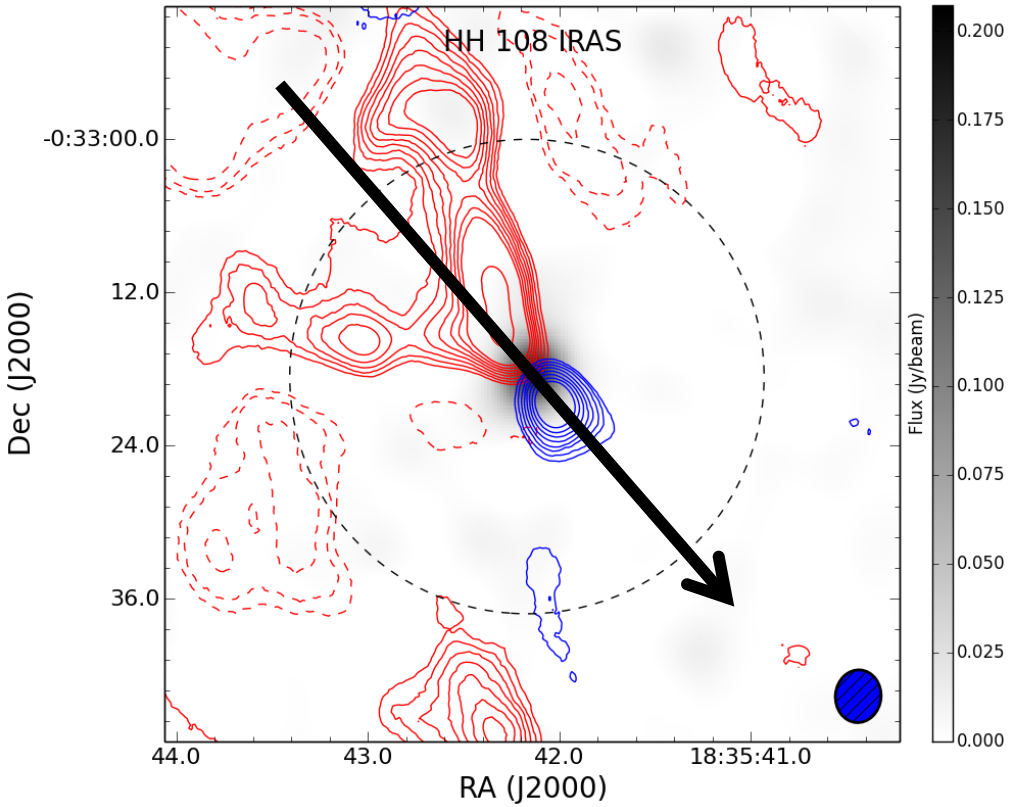
- The shapes of PV diagrams can constrain the driving mechanism of the outflow (Lee et al. 2000)
- **Jet-driven outflow**
  - A PV diagram along the outflow axis shows spur structures with a broad velocity range at the head of the jet

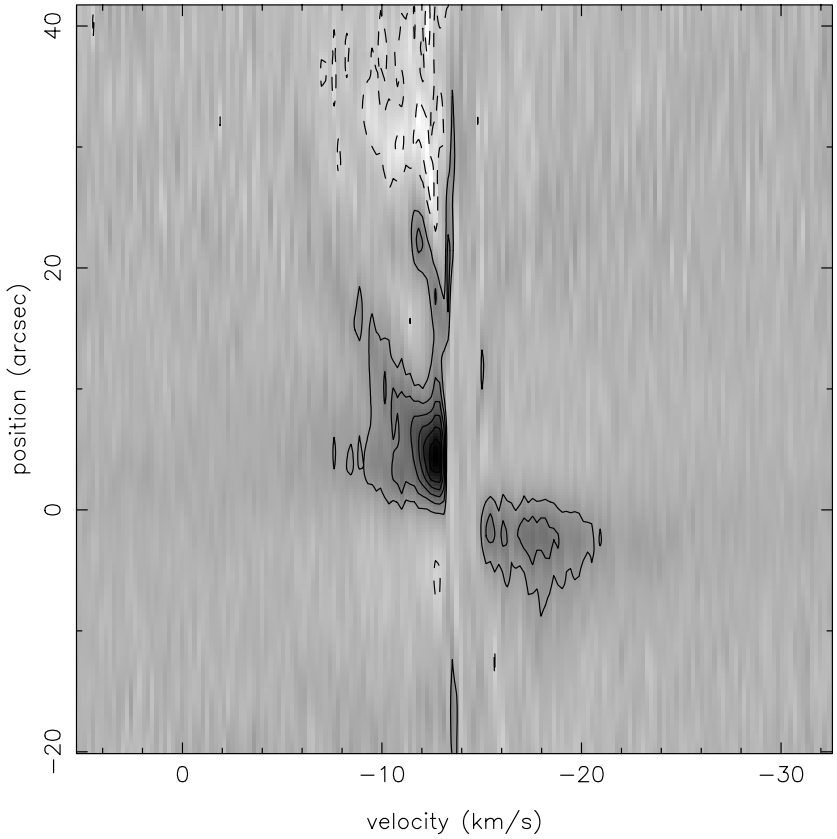




Lee et al. (2000)

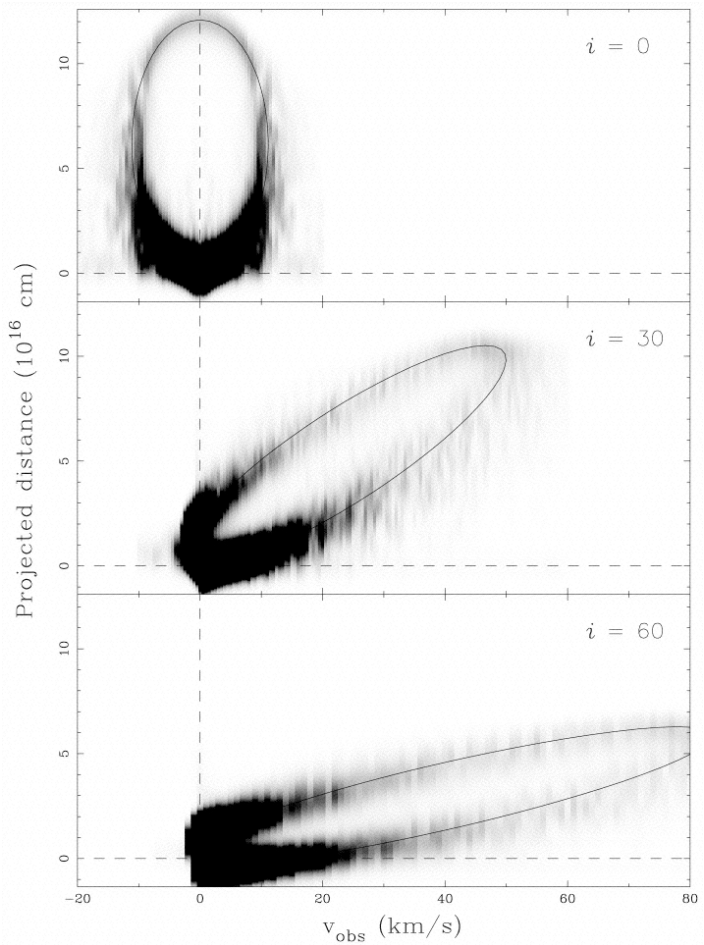
HH 108 IRAS



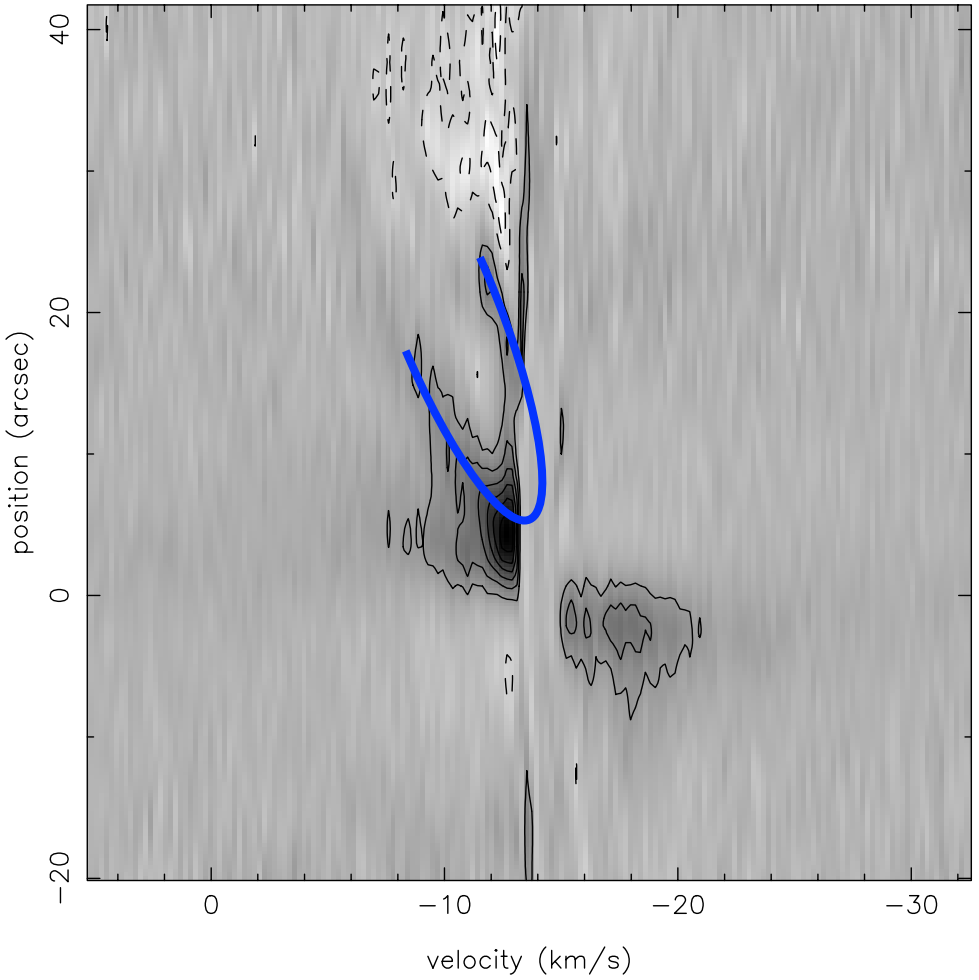


- d ~ 310 pc

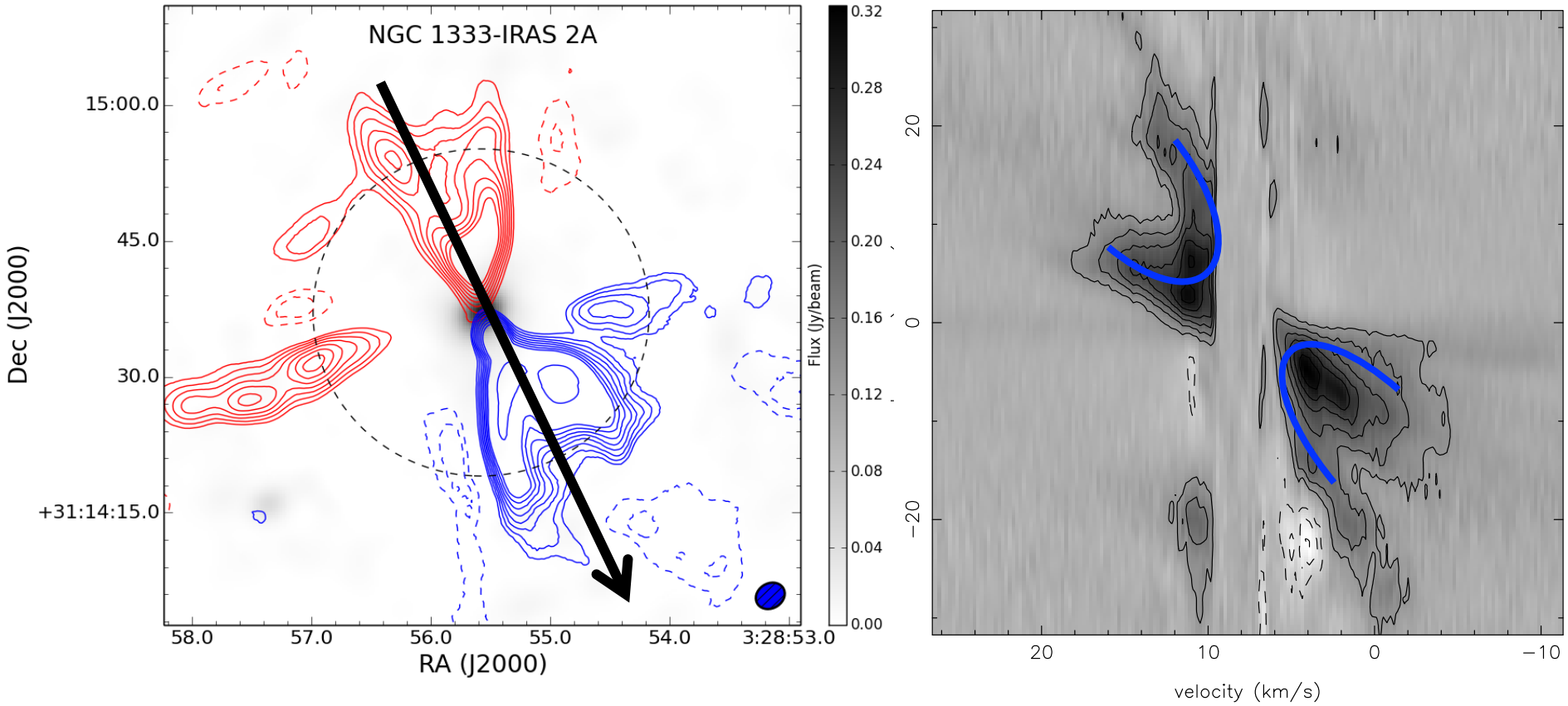
HH 108 IRAS



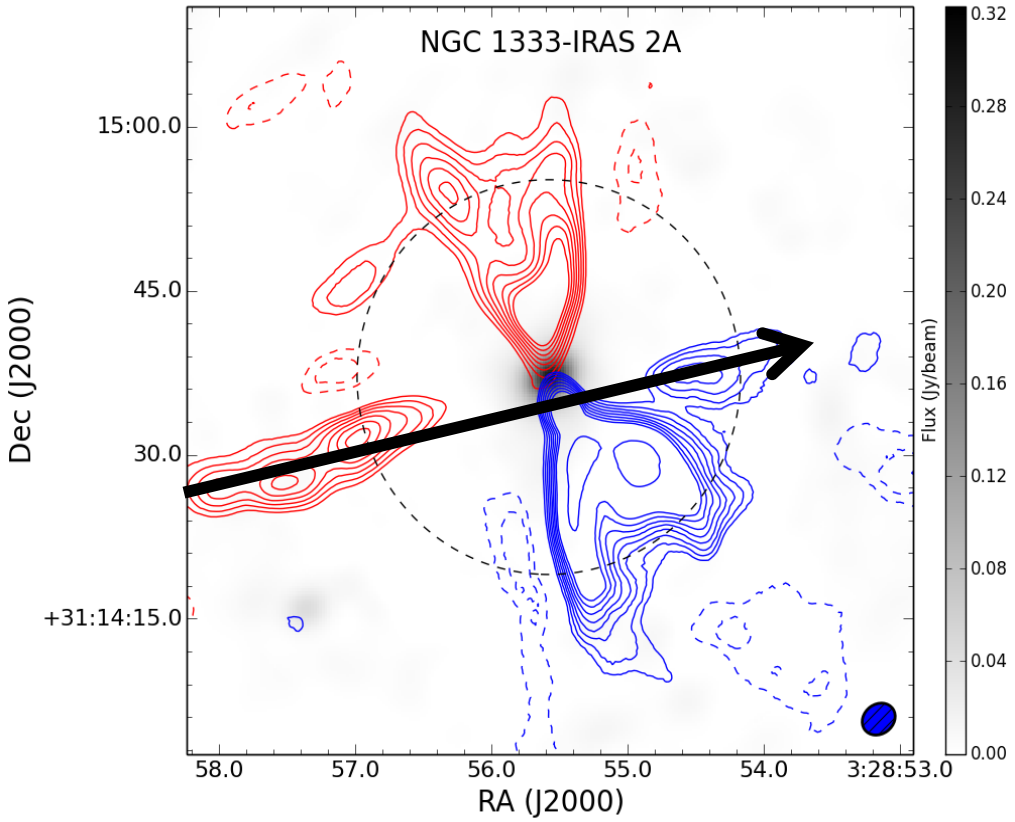
Lee et al. (2000)

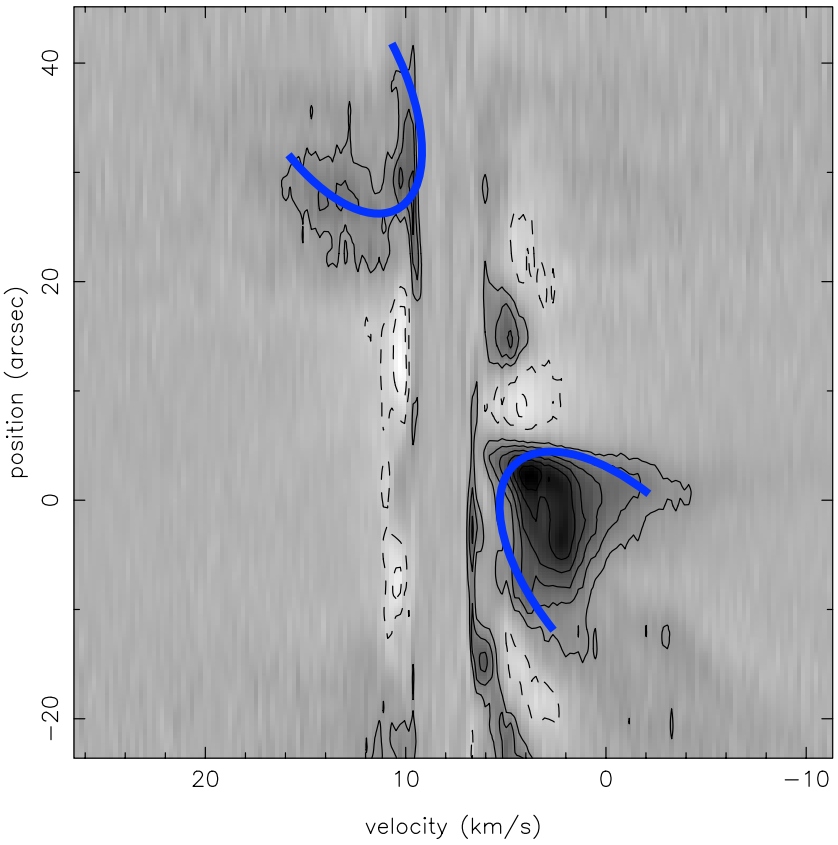


NGC 1333-IRAS 2A



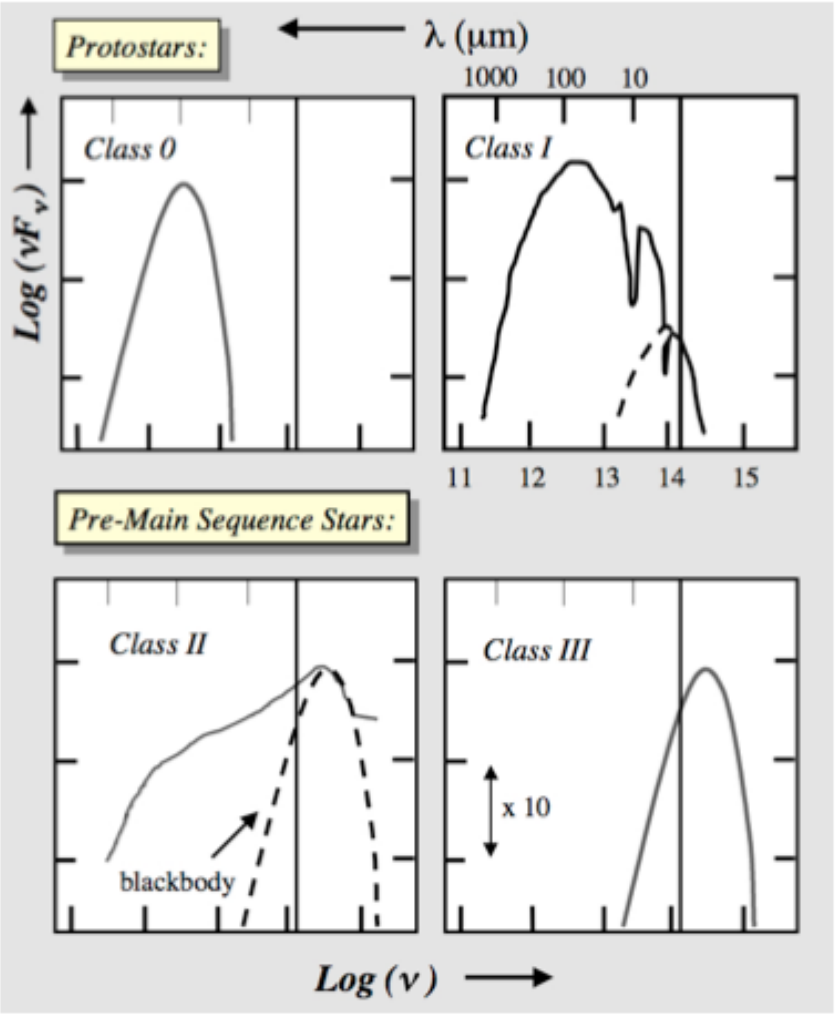
NGC 1333-IRAS 2A





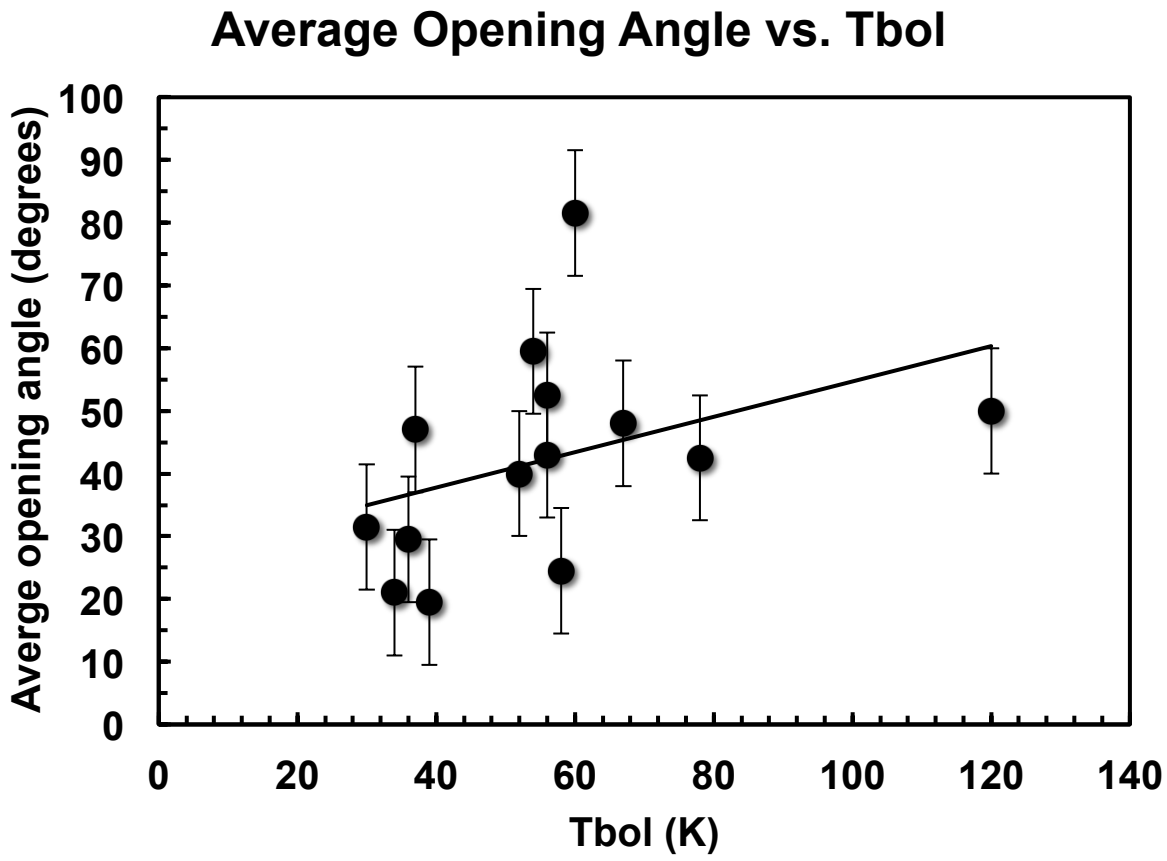
Evolutionary Indicators

- Bolometric temperature (T_{bol}) increases monotonically from Class 0 to Class III sources (Chen et al. 1995)
  - Class 0: $T_{bol} < 70$ K
  - Class I: $70 < T_{bol} < 650$ K
- But the spectral energy distribution peak is not at 1 mm



Lada (1999)

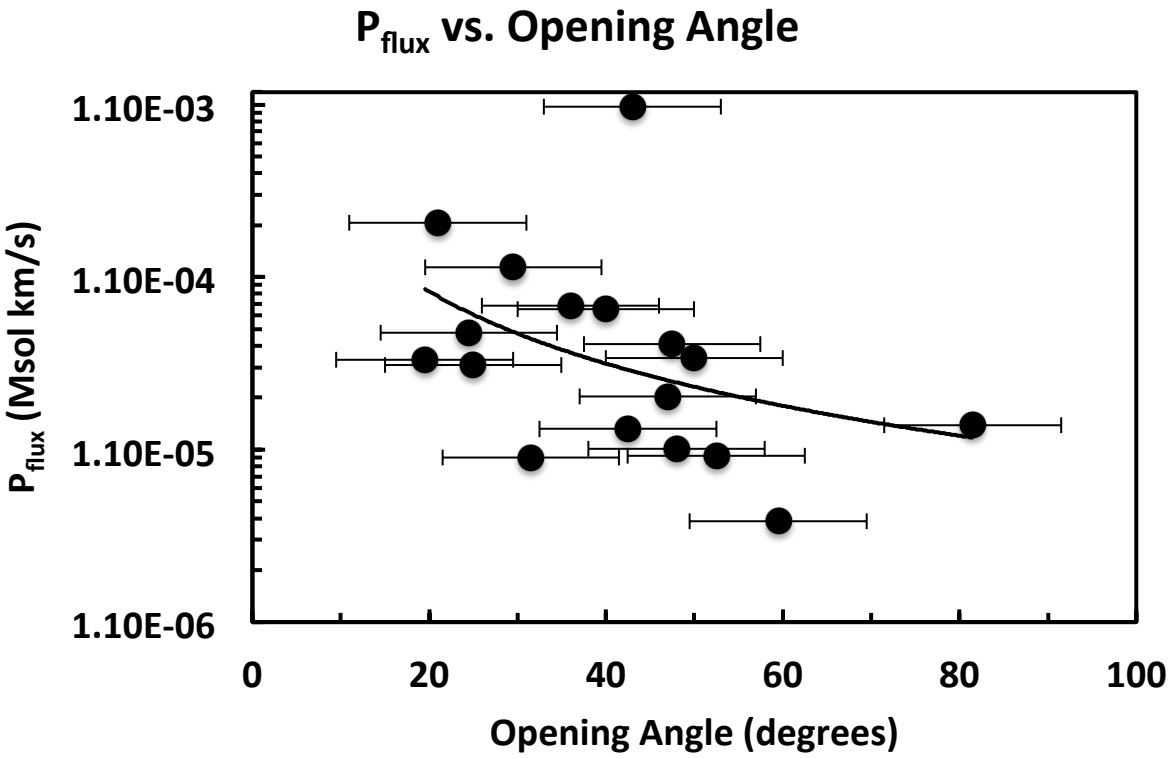
Evolutionary Indicators



See also: Arce & Sargent (2006), Velusamy et al. (2014), Seale & Looney (2008)

Energetics

- Momentum Flux (P_{flux}) should be conserved along the outflow direction if low-mass outflows are momentum-driven (Bontemps et al. 1996)

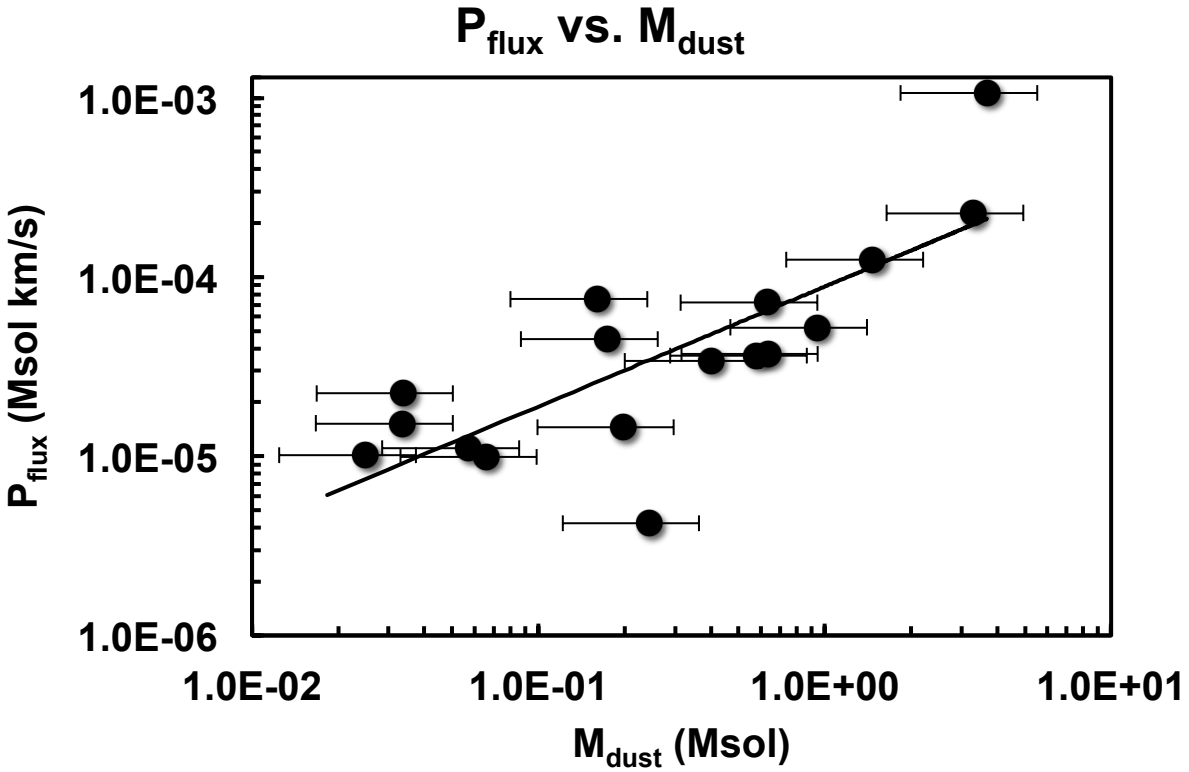


- A decrease of outflow energetics with age

See also: Bontemps et al. (1996), Curtis et al. (2010)

Energetics

- On these scales, $M_{dust} \propto M_{envelope}$
- Younger sources have more massive envelopes
- Previous plot: younger sources have more energetic outflows



Summary

- **Molecular lines (such as CO) are key to understanding outflow properties**
- Binary outflows are often misaligned
- Position velocity diagrams indicate these protostars have wind-driven outflows
- Outflow energetics decrease with source age
- More massive sources have more energetic outflows